Annual Project Summary

USGS Award 05HQGR0007

"CONSTRAINING NONLINEARITY IN STRONG GROUND MOTION USING REPEATING EARTHQUAKES"

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Program Element II. Earthquake Physics and Effects

Research supported by the U.S. Geological Survey (USGS), Department of the Interior, under USGS award number 05-HQ-GR-0007. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.

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CONSTRAINING NONLINEARITY IN STRONG GROUND MOTION USING REPEATING EARTHQUAKES

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Technical Abstract

Seismologists and engineers typically make very different assumptions about wave propagation during strong ground motion. Seismologists often assume that wave propagation is linear, such that commonly assumed principles, such as superposition, apply. Engineers, often assume that wave propagation during strong ground motion is nonlinear, at least in the near-surface of soil sites, and results in a reduction of large amplitude ground motion during strong shaking. Our research is important to both scientists and engineers. It will be important to engineers because it provides independent ground truth to the assumption of strong ground motion nonlinearity. By constraining the factors that control nonlinearity in strong ground motion, it should be possible to improve modelling of such effects. Our research will be important to seismologists because source models derived from strong motion data, particularly for large earthquakes, may be inaccurate and biased, if nonlinearity is ignored.

This proposal was funded to study the depth dependence of nonlinearity using a combination of borehole and surface measurements of earthquakes in Japan. The occurrence of the 2004 Parkfield earthquake during the project period allowed us, with the permission of the program manager, to study just this effect for that event as well. We found that the nonlinearity we observe is almost entirely due to velocity changes in the upper 100 meters of the crust. Over the next three months we will complete our original proposed work on repeating earthquakes in Japan.

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Non-Technical Abstract

The damaging strong shaking in earthquakes is strongly influenced by "nonlinearity" in wave propagation. Nonlinearity, in this context, means that the strength of shaking is not as great as would otherwise be predicted, which is important information for coping with earthquake risk. Under this grant we have exploited a newly developed way to detect such nonlinearity, which uses the signals from small repeating earthquakes, to examine the depth dependence of the effect. We have found that the great majority of nonlinearity, as we can detect it, is very shallow, occurring in the upper 100 meters of the Earth's crust.

Introduction

A great deal of work has been carried out on geotechnical aspects of nonlinear strong ground motion, but although seismologists have found evidence for nonlinear strong ground motion, its interpretation is often ambiguous. Laboratory experiments suggest that at conditions in the shallow crust, nonlinearity should occur for strains exceeding about 10^{-6} (e.g., *Ten Cate et al.* [2000]). Typical earthquake stress drops imply strains of $\sim 10^{-4}$, suggesting that nonlinearity ought to be widespread in the near field of large earthquakes, at least near the Earth's surface.

We have previously used repeating earthquake sequences on the Calaveras and San Andreas Faults in central California to document variations in the velocity of wave propagation in the Earth's crust that were caused by the 1984 M_w 6.2 Morgan Hill and 1989 M_w 6.9 Loma Prieta earthquakes [*Rubinstein and Beroza,* 2004; *Schaff and Beroza*, 2004]. By cross correlating waveforms we can reliably measure changes in the arrival time of seismic waves as small as several milliseconds from NCSN data. Figure 1 shows an example of such a measurement for the same set of repeating earthquakes recorded at two stations: one that shows significant changes and one that does not.

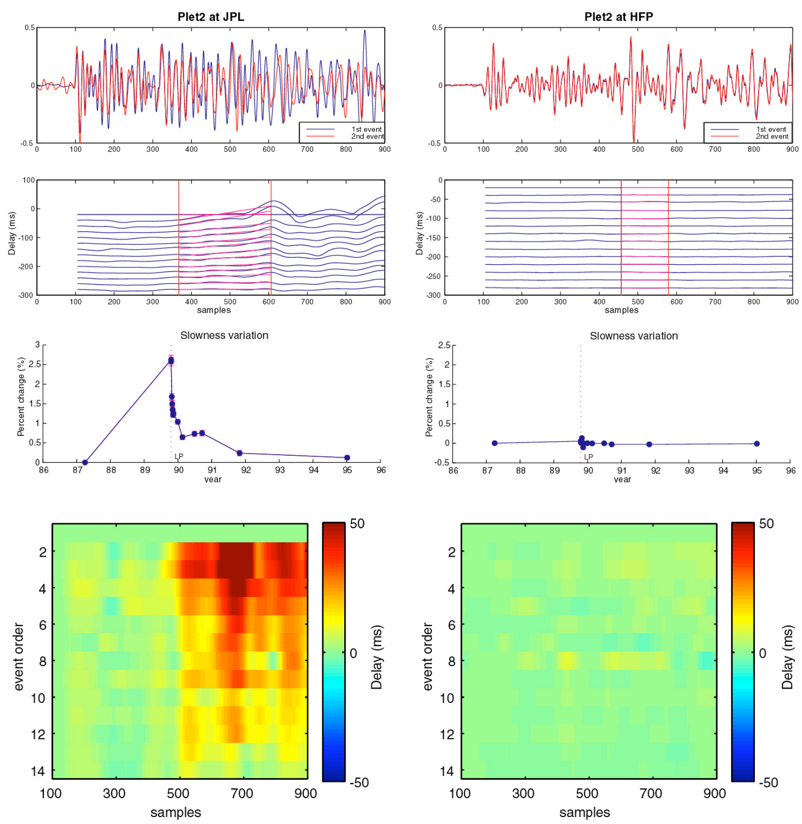

Figure 1. For NCSN stations JPL and HFP, top panels show seismograms. Second panels show results of running-window cross correlation for event pairs. Delays of the second seismogram relative to the first are manifest as upward trends. By fitting a slope to these delays, the signal can be interpreted as a percentage change in the path averaged slowness, shown in the third panel as a function of calendar time. Note large slowness increase at JPL following the Loma Prieta earthquake. Final panels show delays as the second panel, but in a format that is easier to view as part of a map display.

We use the two target repeating earthquake sequences of the SAFOD experiment to identify time varying properties of the shallow crust in the Parkfield area at the surface and in shallow boreholes. At the surface, we find that the 2004 Parkfield earthquake caused direct S wave delays exceeding 7ms, and S coda delays exceeding 15ms. We attribute these delays to cracks formed or opened during the strong shaking of the Parkfield earthquake. Observations at depth show that the direct S wave arrival time was much less affected by the Parkfield earthquake. This provides evidence that damage caused by strong shaking (nonlinear strong ground motion), is limited to the near surface (<100m).

Cross-correlation measurements reveal that the member events of both repeating earthquake sequences are located within meters of each other. The two repeating sequences are separated by approximately 60 m along the San Andreas Fault [*Nadeau et al*., 2004]. Prior to the 2004 M6 Parkfield earthquake, these repeating earthquake sequences appeared to be linked, often recurring within 24 hours of each other. Both events repeated, approximately one year prior to the Parkfield earthquake, on October 21st and 22nd 2003. Since the Parkfield earthquake, one has repeated twice, the other three times: they both repeated on September 28, 2004 (two days after the mainshock) and one sequence repeated October 24, 2004 and January 23, 2005, while the other repeated December 8, 2004. We examine these events using two seismic networks: NCSN, a network of high gain, short period, surface seismometers that record at 100 samples per second and HRSN a network of short period, shallow borehole seismometers (~70-350m depth) that record at 250 samples per second

Although we find that delays are largest in the S coda (Figure 2b, 3), we choose to examine the delay of the direct S arrival. This provides a measure of the change in seismic velocity near the station that is relatively insensitive to scattering, unlike coda measurements. We treat the S delays observed for the repeats immediately following the Parkfield earthquake as the coseismic change in delays. In doing this, we make the assumption that between October 2003 and the 2004 Parkfield earthquake there was no significant change in seismic velocities. Processes associated with aseismic transients have been shown to influence wave propagation [Niu, et al, 2003], however, no such transients were observed in this area between October 2003 and September 2004 [J.R. Murray, pers. comm., 2005].

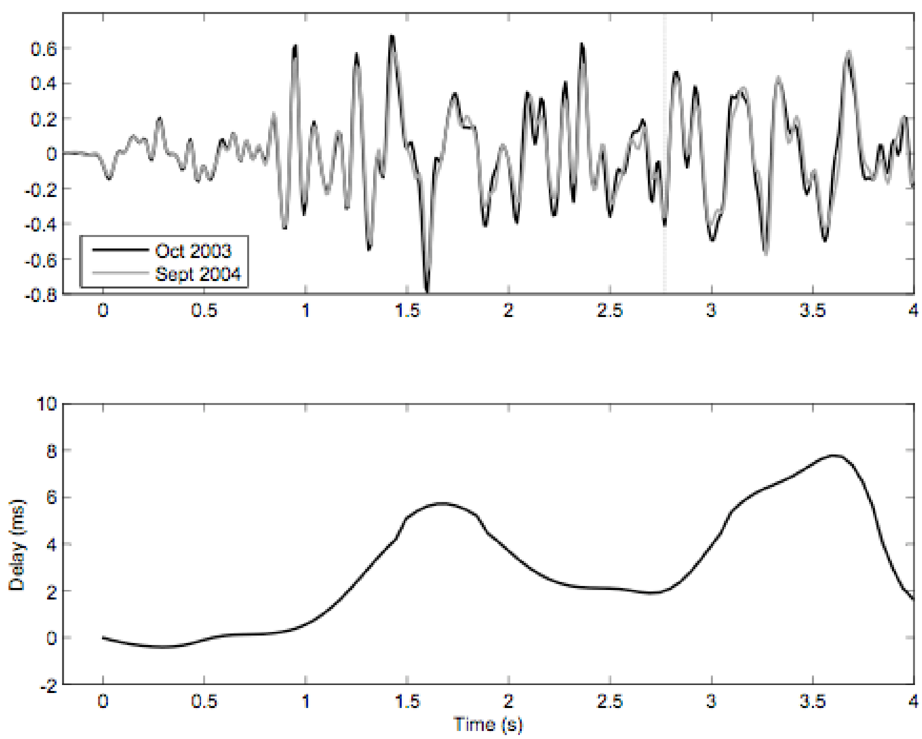

Figure 2: (a) Repeating earthquake sequence 2, as recorded by NCSN station PHF. Vertical, dashed line indicates S Arrival. (b) Delay of September 2004 repeat of sequence 2 at PHF relative to October 2003 repeat.

In this time period, the 2003 San Simeon earthquake also occurred nearby, so its influence must be considered. Unfortunately, we don't have the temporal resolution to measure any effect of the San Simeon earthquake, which implies that our "coseismic" measurements could be overprinted We have previously shown that earthquake induced seismic velocity changes heal logarithmically with time [Rubinstein and Beroza, 2004a,b; Schaff and Beroza, 2004]. This indicates that any effect that San Simeon earthquake had on local seismic velocities would be mostly healed by the time the Parkfield earthquake occurred. For these reasons, we believe that the change in seismic is related to the Parkfield earthquake.

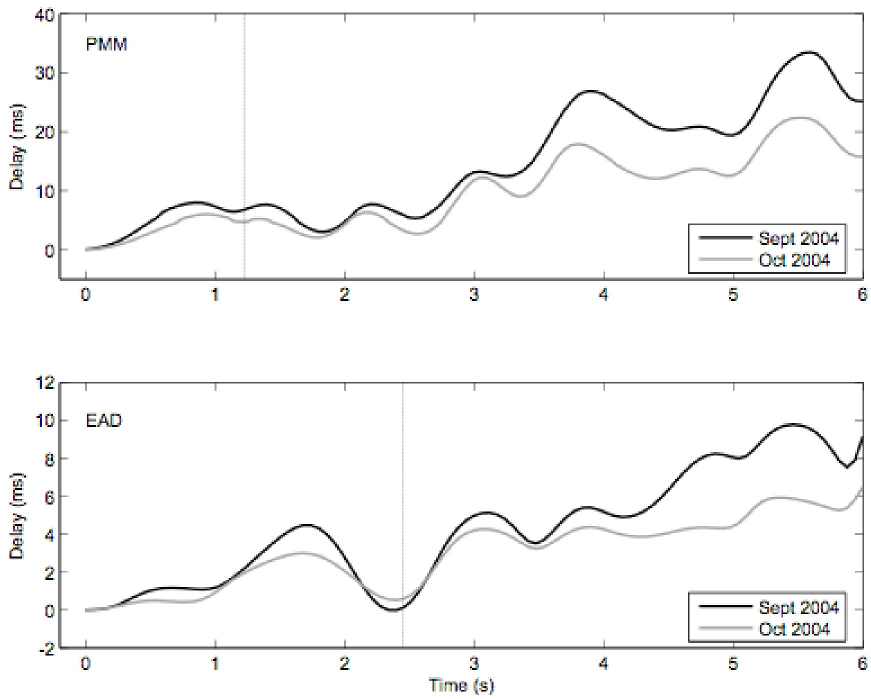

Figure 3: Delay of September and October 2004 repeats of repeating earthquake sequence 1, relative to October 2003 repeat at NCSN station PMM and HRSN station EAD.

Surface Stations

From the correlation analysis, we find significant delays caused by the Parkfield earthquake that vary in strength throughout the seismogram (Figure 2,3a). We observe this at many of the NCSN stations. The delays are largest in the S coda, exceeding 25ms at PMM. Delays are significant for many other parts of the seismogram, including the direct S arrival, where S delays can exceed 7ms (e.g., PMM). In the second repeat of both repeating earthquake sequences after the Parkfield earthquake, we find the delays decrease significantly throughout the seismogram (Figure 3a). This implies that the local damage is healing with time.

Borehole Stations

Our observations at the HRSN stations are significantly different than those for the surface seismometers (NCSN). We typically find that there is little or no delay (<2 ms) in the S arrival following the Parkfield earthquake (Figure 3b, 4). Similar to the NCSN stations, at many of the HRSN stations we observe delays in the P and S codas that increase with time into the coda (Figure 3b). For those borehole stations that observe delays in the P and S codas, we find that the coda delays show healing between the first and second repeats (Figure 3b).

The different behaviors of the delays observed at NCSN (surface) stations and HRSN (borehole) stations, suggests that the upper 100m of the Earth's crust responds differently to strong ground motion than do deeper materials. The relation between strong ground shaking and S delays for the two networks accentuate this point, as we see a clear scaling between strong ground motion and S delays for the surface stations and no scaling of S delays to strong ground motion for the borehole stations. We don't observe a scaling of S delays to strong ground shaking at depth because the borehole records are from far below the shallow layers damaged by the Parkfield earthquake (Figure 3b, 4).

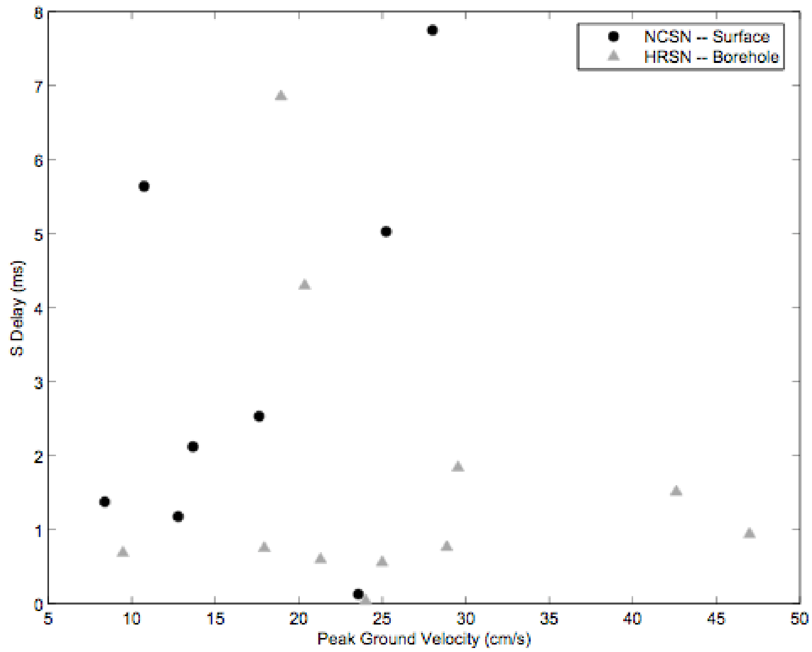

Figure 4: Coseismic S delay of each station plotted against peak ground velocity experienced in the 2004 Parkfield earthquake. The S delay is the mean of the measurements computed for the September 2004 repeats of both multiplets relative to their October 2003 repeats.

To explain the delays observed at the NCSN stations, we appeal to a model in which the strong shaking of the Parkfield earthquake caused cracks to grow and/or open near the surface, effectively damaging the medium (nonlinear wave propagation). This model was first suggested to explain reductions in seismic velocity coincident with the Loma Prieta and Morgan Hill earthquakes [Rubinstein and Beroza, 2004a; Schaff and Beroza, 2004]. The behavior of our observations of phase delays induced by the Parkfield earthquake parallel those delays induced by the Loma Prieta and Morgan Hill earthquakes: S delays scale with strong ground shaking, delays decrease with time following the mainshock, and delays are largest in the coda. Unlike the surface stations, we see no scaling between peak ground velocity in the Parkfield earthquake and the delays of the S arrival for the HRSN borehole stations, but instead see that the Parkfield earthquake does not affect S arrival times. Because the S-P time stays consistent before and after the Parkfield earthquake, we believe that there are no velocity reductions local to the HRSN borehole stations. This implies that the strong shaking of the Parkfield earthquake is not causing damage at depths of ~100 m. What delays are present in the S and P codas, we attribute to scattered energy that is coming from nearer the surface where nonlinear strong ground motion has reduced seismic velocities. This suggests that even the relatively small confining pressure that rocks are under in the shallow boreholes of the HRSN is enough to prevent damage by the passage of strong seismic waves. Some suggest that damage caused by the passage of seismic waves, the same phenomenon that we study here, is responsible for triggering of earthquakes at large distances [Gomberg and Johnson, in review; Johnson and Xia, in review]. Our findings that show that strong shaking does not damage earth materials at modest depths (100-300m) suggest that for this triggering model to be valid, pore fluid pressures would have to be nearly lithostatic, such that the effective stresses were comparable to those at 100m depth.

We have used repeating earthquakes near Parkfield to identify near surface reductions in seismic velocity. Specifically, we identify delays in S arrival times at surface stations, and the general absence of delays at shallow borehole seismometers (depths ~100-300m). The depth dependence of the S delays implies that the pressure at the depth of shallow boreholes prevents strong shaking from damaging rocks at depth. This allows us to conclude that nonlinear wave propagation and the damage that it induces is limited to the very near surface or to regions of particularly high pore fluid pressure.

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Publications resulting from this grant to date include:

2005 Rubinstein, J. L., and G. C. Beroza, Depth Constraints on Nonlinear Strong Ground Motion from the Parkfield Earthquake, Geophys. Res. Lett., **32**, doi:10.1029/2005GL023189.